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PRELIMINARY REPORT ON THE FEASIBILITY OF HIGH POWER ELECTRONIC WARFARE (EW) USING EXPLOSIVE ENERGY SOURCES

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MATERIALS RESEARCH LABORATORY

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G.A. Clark and D.R. Sadedin*

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ABSTRACT

Electronic warfare (EW) is an extremely important element in modern military conflicts. One form of EW involves jamming, where in general the effectiveness increases with the power level that can be employed. Within the constraints of the upper power limit it would seem to be possible to raise power levels to the point where components are damaged. The required high powers for such EW functions can be produced by compact magnetohydrodynamic (MHD) power sources using fuels such as explosives and propellants. Some indicative applications are discussed and areas for research are identified.

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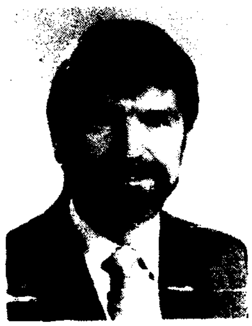


Gregory Clark was born in Melbourne in 1950 and joined MRL in 1972 where he initially worked in the areas of metrology, laser research and electronics. After obtaining a Bachelor of Applied Science (Physics) from RMIT in 1979 he joined the Explosives Division undertaking experimental and theoretical research in the field of electromagnetic propulsion; an area in which he has published a number of scientific papers and reports. In 1986 he moved to the Materials Division researching defence applications and significance of retroreflection. He is now an Experimental Officer Class 3, undertaking experimental research into non-linear optics and radar absorbing materials.

David Sadedin was born in Adelaide in 1937. He was a Technician in Training and later a Cadet Engineer in the Department of the Postmaster General. He completed his degree in electronic engineering in 1962 and joined MRL in 1966, where he worked in the Engineering Design Office until 1980 and then in the Physical Chemistry and Physics Divisions. In 1987 he joined the CSIRO. Since 1980 he has worked mainly upon Electromagnetic Launching (EML). In 1987 he was awarded his PhD in Electrical Engineering for his thesis on aspects of EML. At CSIRO he is engaged in commercial applications of EML technology.

CONTENTS

PRELIMINARY REPORT ON THE FEASIBILITY OF HIGH POWER ELECTRONIC WARFARE (EW) USING EXPLOSIVE ENERGY SOURCES

1. INTRODUCTION

Electronic warfare (EW) techniques have assumed increasing importance since World War 2 and recent military conflicts have confirmed that importance. In 1973, for example, the Israeli Airforce lost many aircraft due to Russian SAM missiles which had been updated and were not detected by the Israeli EW equipment [1].

Jamming of transmissions from enemy control and communications links, and from radar surveillance and tracking systems are some of the methods used in electronic warfare. In general the greater the power which can be employed, the more effective will be the disruption and the greater will be the effective operating ranges achieved.

If the power could be increased sufficiently, actual damage could be done to the components and semiconductor devices which are used in modern electronic equipment. The damage incurred is caused by the direct coupling of the radiated energy into electronic circuitry. If enough energy can be coupled into the circuitry, semi-conductor junctions will be electrically punctured and destroyed. The equipment would then remain out of action instead of recovering after the jamming ceases.

The energy and power required to damage semiconductor devices are known from nuclear electromagnetic pulse (EMP) studies [2]. Representative energy and power flux levels are about 1 J/m^2 and 1 MW/m^2 respectively [3]. The realization of such power densities at potentially useful distances (say 100 to 1000 m) from the radiating source is not practicable using conventional power sources, such as generators or batteries.

Explosives, and similar substances such as propellants and hydrocarbon fuels release chemical energy at rates which are compatible with the flux levels mentioned above. The energy, however is released in thermal form instead of electrical. Methods to convert the chemical energy of explosives and such-like substances into high power electrical pulses have been under development for about thirty years. Two approaches have been tried; pulsed magnetohydrodynamic (MHD) and magnetic flux compression conversion. Typically 5%, and up to 15% [4], of the chemical energy of the explosive-type substance can be realized as electrical energy by these methods.

A comprehensive literature exists on both methods, including accounts of a pulsed magnetohydrodynamic system particularly directed at the high power EW possibilities discussed above [5, 6].

This report deals with the fundamental feasibility of, and indicates applications for, high power EW weapons and the explosives-type generators which might be used to supply the necessary high power. A complete study of high power EW must also deal with the high-power high-frequency oscillators, the antenna used to radiate the power and with other topics referred to in the final part of this report.

This report is divided into 9 sections. Following the introduction in Section 1, Section 2 deals with the potential of explosive-type generators to produce large pulses of electrical power. Section 3 suggests possible EW applications of such power generators for the Australian Defence Force (ADF). The basic theory behind the two general types of generators is explained in Section 4 together with their operating advantages and disadvantages. Sections 5 and 6 discuss military MHD research performed over recent years and the key technical areas related to the MHD generator, the RF generator and the antenna. Section 7 presents a summary and conclusion which is followed by references, a small bibliography of pulse-power research and a symbols table in Sections 8, 9 and 10 respectively.

2. POTENTIAL FOR THE PRODUCTION OF A HIGH POWER RADIATION USING EXPLOSIVE-TYPE ENERGY SOURCES

The calculations in this Section demonstrate the potential that exists for high power EW applications, based upon the reported conversion efficiency of 5% for explosives-type power sources.

One kg of an explosive such as TNT releases 5 MJ of thermal energy in about 10 μs. Taking the typical value of 5% for the conversion to a raw DC electrical pulse that is produced simultaneously with the production of the thermal energy, the electrical energy is 250kJ and the average electrical power is 2.5×10^{10} W.

If the above explosively generated electrical energy is converted to omnidirectional electromagnetic radiation with an efficiency of 50%, the energy flux density (ϕ_E) at a distance of 100 m from the explosion is

$$\phi_E = 125 \times 10^3 / 4\pi \, (100)^2 \ \mathrm{J/m^2}$$

which is approximately 1 J/m^2. Since the energy is generated simultaneously with the explosive energy release, ie. in 10 μs, the average power density of the radiation is 10^5 W/m^2 at a distance of 100 m from the source.

The above value of 1 J/m^2 is known to cause damage to electronic components, as was mentioned in the Introduction, but the power level is a factor of 10 too low. This problem can be overcome in principle by the use of a directional antenna. If an antenna with a gain of 20 dB were used to focus the radiation towards its target, the intensity of the radiation at 100 m from the source would be increased to 100 J/m^2 at a power of 10^7 W/m^2. At such energy and power levels damage would almost certainly occur in all but the most highly protected semiconductor-based electronic systems.

The use of a directional antenna would also increase the range at which damage could be achieved, particularly in less highly protected electronic systems. Thus, using an antenna with a gain of 20 dB as mentioned above, the energy flux at 1 km would be 1 J/m^2.

12. Swallom, D.W., Sonju, O.K., Meader, D.E. and Haskey, G.T. (1977)

In addition to the energy and power estimates, we can utilize the 5% conversion value to estimate the mass of the power source, which would be the dominating mass in the total weapon system. As is shown elsewhere [7], the mass of a system can be roughly estimated from the energy which it encloses. A conservative estimate is 10 kJ of energy per kg [7] of containment structure. The energy released by 1 kg of TNT, viz, 5 MJ, would thus imply a mass of 0.5 tonne.

In summary, these calculations indicate that a high power EW system capable of inflicting damage upon electronic apparatus at distances of a kilometre or more may be possible utilizing an explosive-type pulse power source and that the system mass could be of the order of 1 tonne.

To conclude this Section, some further comments are given in relation to propellants, high frequency generating devices, antennae and the possible superiority of high power EW over conventional projectiles.

(i) Both explosives and propellants can each release approximately 5 MJ of thermal energy per kilogram. Explosives can release this energy in a time interval varying between 10 μs to 1 ms whereas propellants release energy more slowly, typically in a time ranging from less than a millisecond to seconds. One kg of an explosive such as TNT releases 5MJ of thermal energy in about 10 μs. If 5% of this energy is converted to raw DC electrical energy with a 50% conversion efficiency to radiated electrical energy, the radiated electrical energy is 125 kJ and the average power is 1.25×10^{10} W. If 1 kg of propellant is burned in 1 second with an equivalent conversion efficiency, the radiated electrical energy is the same but the average power is only 125 kW. Clearly, in a high repetition-rate, high power pulse-mode, the use of explosives as the primary energy source would be preferred.

(ii) The conversion of the explosively generated DC electrical energy to electromagnetic radiation can be efficiently achieved by a microwave oscillator such as a magnetron [8]. Gilmour [9] has reported magnetrons having efficiencies between 50 and 85% achieving GW pulse levels. It must be noted that these efficiencies neglect the power dissipated in power supplies and magnetic focussing systems associated with microwave oscillators.

(iii) Intensity gains in the radiated energy will be governed by the antenna, the construction of which will also be determined by other factors such as the jamming frequency, the directionality required and the electrical breakdown of the air surrounding it. (The breakdown strength of air, 3 MV/m, limits the radiated power flux to 10^{10} W/m^2). A further consideration is the acceptable level of rearward and leakage radiation from the antenna which can be tolerated by the platform.

For best effect it seems likely that the jammer frequency should be matched to the operating frequency of the target electronic system to be disrupted. Energy would then be coupled into the target by the transmitting and/or receiving antennae. In this case energy densities above 1 J/m^2 would be likely to cause damage to front end semiconductor components whilst 100 J/m^2 would certainly cause damage. If the jamming frequency is not matched to the operating frequency of the target, coupling could be less efficient via the front end but energy could nevertheless still enter the system by antenna and other ports and couple energy into wire harnesses, circuit board conductors and semiconductors directly. Although energy coupled into the system this way might not cause physical damage, the higher levels would still be expected to disrupt electronic system operation.

(iv) The conversion of explosive energy to electromagnetic radiation could in some important applications be more effective than the conventional use of projectiles against sea-skimming missiles. Using a focussed, directed (20 dB) beam approach and scaling from the above calculations, 50 kg of explosives could be used to produce a high frequency field of 50 J/m^2 at 1 km, which would disable the missile's electronic systems. For the lower damage thresholds mentioned above, the effective range could in principle be tens of kilometres. Such ranges would be required to counter very high velocity missiles. Alternatively, if a damage range of 1 km is acceptable then a smaller explosive mass could be used (e.g. 10 kg to produce 10 J/m^2 at 1 km).

Other advantages are:-

1. The destructive radiation exists throughout a conical volume emanating from the antenna. A narrow cone of radiation is preferred (consistent with pointing accuracy) as this increases power density at the target, increases range and reduces the probability of damage to friendly platforms.

2. Transit time between the antenna and the attacking missile is practically zero (speed of light velocity $\simeq 3 \times 10^8$ ms^{-1}).

3. Aiming would be easier because of the radiation pattern (conical volume) and the radiation velocity.

(v) Gill et al [10] have performed design calculations for a reusable pulse power MHD source (PPMHD) which would use 0.94 kg of OCTOL ($\approx$ 5 MJ of energy). For a test bed facility they calculated a 415 kg mass for the PPMHD power supply. This device would produce 65 kJ at 2.24 GW of peak electrical power. It was further projected that within 4 years the developed device would yield about 500 kJ at a power level of 13 GW and the total mass would be under 300 kg.

3. INDICATIVE HIGH POWER EW APPLICATIONS

From the above Section it follows that the generic EW system would be made up of the five main elements which are shown in Fig. 1, viz.,

(i) The explosive or other fuel which stores the prime energy of the system in chemical form;

(ii) the device which converts the (thermal) energy released from the explosive or other fuel into a DC electrical pulse;

(iii) the means of converting the DC electrical pulse to voltages that suit the device which generates the high power RF;

(iv) the high power RF generator;

(v) the antenna which directs the RF towards the target.

The generic system could be realised in various specific forms to suit different needs. Three representative, though not necessarily practicable systems, are discussed below in order to suggest the type of operational applications which might be considered.

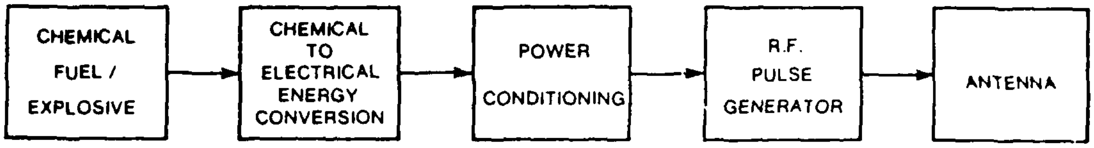


Figure 1 Main components of a chemically-powered EW system.

The first application relates to aircraft self-protection jamming. The system could perhaps utilize the 20 mm cannon carried by the F111 aircraft. It has been reported that a 30 mm cartridge can be used to generate 10 kJ, 1 GW electrical pulses, [6]. Using an equivalent energy source, an area having a diameter of 100m could be illuminated with a high frequency energy flux of 1 J/m^2 at a rate of 10^5 W/m^2. With a suitable scanning antenna system, useful target areas on the ground could be illuminated at a distance 1 km ahead of the aircraft. Since the cannon can fire tens of rounds per second, a corridor many hundreds of metres wide could be covered at a distance of 1 km from the aircraft. Such repetitive firing could be used to counter hostile surveillance, communications, control and weapons systems. The matter of preventing interference to the aircraft's own electronic systems from the antenna's rearward and leakage radiation is of course of vital concern.

A second application involves a missile or projectile launched ahead of the aircraft into the target area. This could carry a much greater quantity of explosive than a cartridge. It could be deployed against radar-controlled anti-aircraft installations and communications centres, either on the ground or in ships. Such systems might be focussed or, more probably in simple weapons, arranged to radiate omnidirectionally depending on the application. These systems would probably only need to be single shot devices although multi-shot applications can be envisaged.

A third potential application is as a point-defence weapon for use against guided missiles or aircraft. It could be mounted, say on a ship, as a multiple-shot focussed directed energy weapon or built as an EW warhead into an anti-missile missile in an omnidirectional single shot form. Another version might be based upon a mortar, enabling it to be used by ground troops.

4. BASIC PRINCIPLES OF POWER SOURCES

As was indicated earlier, the power source is one of the key elements in a high power EW weapon. Two types of systems appear to be suitable for applications requiring compact power sources. These are magnetohydrodynamic generators and flux compression systems.

A literature search has located several thousand unclassified reports on MHD generators whereas flux compression reports are numbered in the low hundreds. Fewer than 50 classified reports on either subject, have been identified.

A general description of MHD generators and flux compressors is presented below.

4.1 MHD Generators

MHD generation is based on Faraday's principle relating to a conductor crossing a magnetic field. Such a conductor has an electric field impressed along its length. The electric field generated is proportional to the velocity of the conductor and the magnetic field. Specifically, the law is:-

$$\underline{E} = \underline{v} \times \underline{B} \tag{1}$$

where $\underline{E}$ = the induced electric field in the conducting medium,

$\underline{v}$ = the velocity of the conducting medium

and $\underline{B}$ = magnetic field cut by the conductor.

A schematic diagram of an MHD generator is shown in Figure 2 [9].

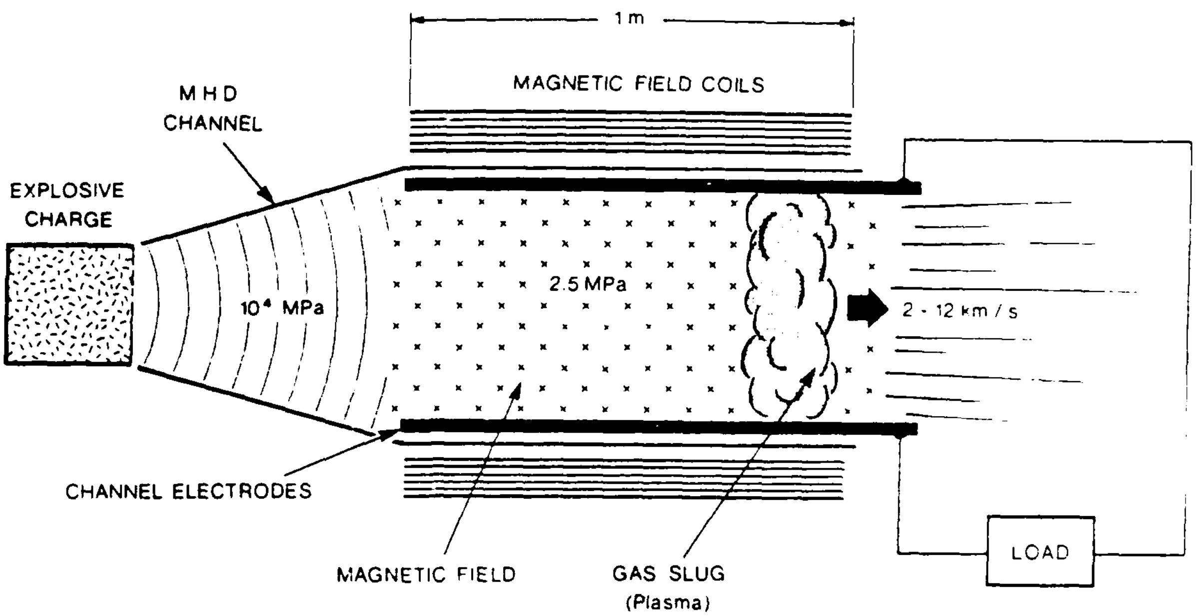


Figure 2 Schematic of an MHD generator.

In Figure 2, a conducting medium, in this case a plasma (highly ionised gas), flows through a channel between two conducting plates. A magnetic field is provided orthogonal to, and between, the plates. The plasma is equivalent to a conductor crossing the magnetic field. The electric field generated in the plasma causes a voltage between the two plates. The voltage thus generated will cause current to flow through the plasma into an external load.

The current flow induced in the plasma interacts with the magnetic field and exerts a force opposing the plasma flow. The mechanical work performed by the flow of plasma against this opposing force is converted in part to electrical energy which is produced by the system.

The maximum power density (P_D) obtainable from the plasma flow through the MHD duct is given, [11], as

$$P_D = 1/4 \; \sigma \; v^2 \; B^2 \tag{2}$$

where σ = plasma conductivity

v = velocity of plasma through the duct

and B = magnetic field

Thus for a given magnetic field, the power is determined by the plasma conductivity and the velocity squared. For reasons of power extraction efficiency, the plasma conductivity must be high so electrical power is not uselessly expended in the plasma. For weakly ionised gases in thermal equilibrium the plasma electrical conductivity varies approximately as exp $(-e \, U_i/k_B T)$, where e is the electronic charge, U_i is the ionisation energy, k_B is Boltzmann's constant and T is the plasma temperature. Thus high temperatures and low ionisation energies will yield plasmas with high conductivity. In order to achieve high conductivity when plasma temperatures are low, the plasma is seeded with the elements of cesium or potassium which have low ionisation energies. The concentration of this seeding is about 1 mol % [11].

Plasma flow through the MHD channel can be either continuous or pulsed [12]. Continuous plasma flow can be produced by the high temperature combustion of fuels, eg toluene and oxygen [13]. The exhaust of rocket motors has also been used. In the pulsed mode, the plasma is generated by explosives, [14]. Either specially "seeded" explosive products form the plasma source, or the explosive energy is used to compress a separate gas which is directed through the MHD channel. Noble gases such as xenon or argon are used in the latter case. It has been reported [5] that Artec Associates in the USA have in this way produced 10 GW of electrical power from a 7 x 17 inch cartridge. As mentioned previously, efficiencies in converting the fuel energy to electrical energy are typically 5%.

Some features of MHD generators are:

(i) they can operate in either a continuous or pulse mode thereby permitting a range of applications,

(ii) pulsed systems can produce extremely high power levels with large energies,

(iii) explosively-driven systems can be very compact,

(iv) the technology, though complex, appears to be approaching maturity for deployment as a pulse power source,

(v) the source impedance is essentially constant in contrast to that of a flux compression generator. This makes energy transfer to a load more efficient.

4.2 Flux Compression Generators

This form of power generation has only a one shot pulse capability. The principle of operation is based on the storage of energy within the magnetic field of an inductor followed by the rapid reduction of the inductance by physically deforming the inductor using explosives [14,15]. Figures 3 and 4 show two ways of doing this. An initial current is caused to flow in the inductor by means of a capacitor bank. The explosives deform the inductor against the magnetic forces and convert some of the explosive energy to additional magnetic energy.

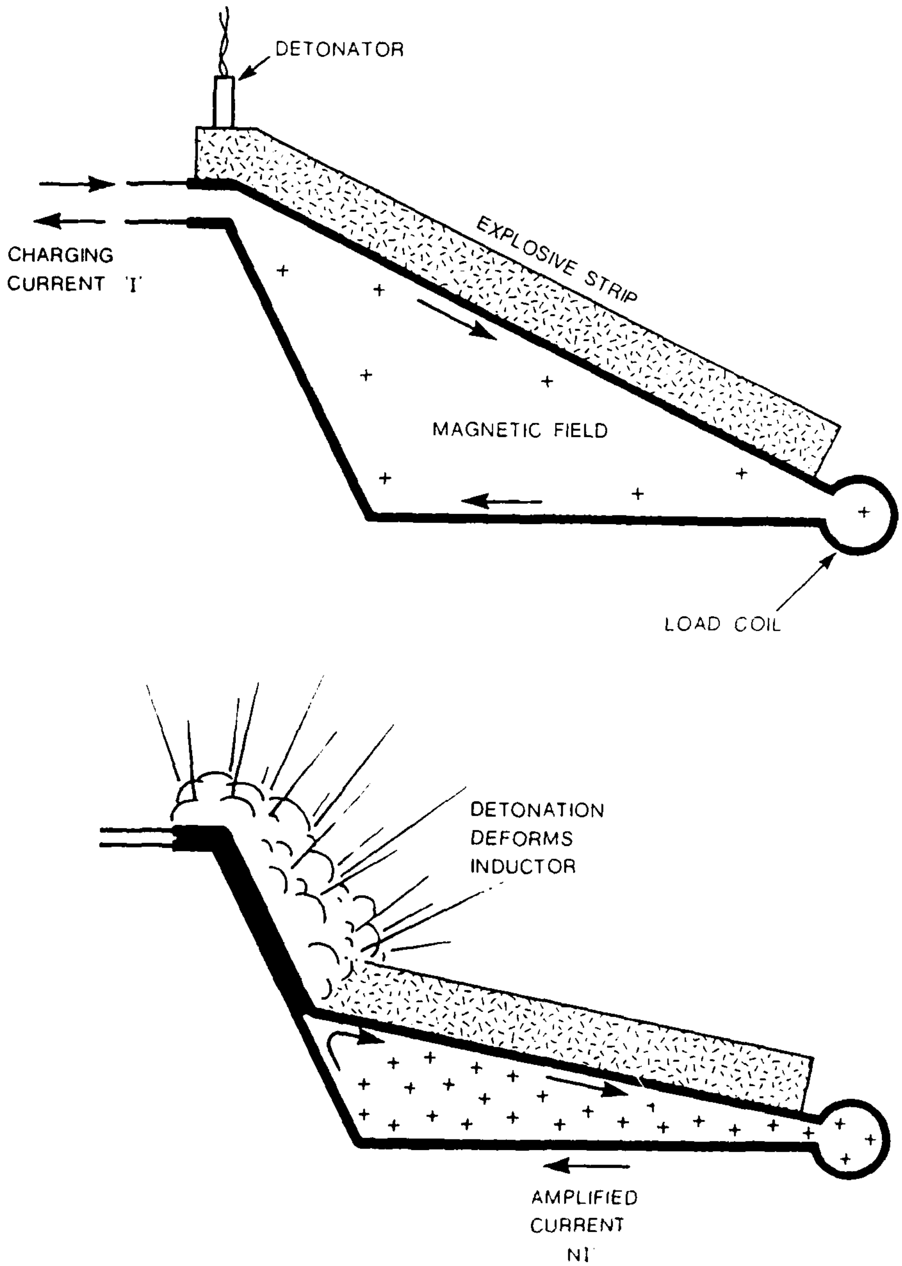
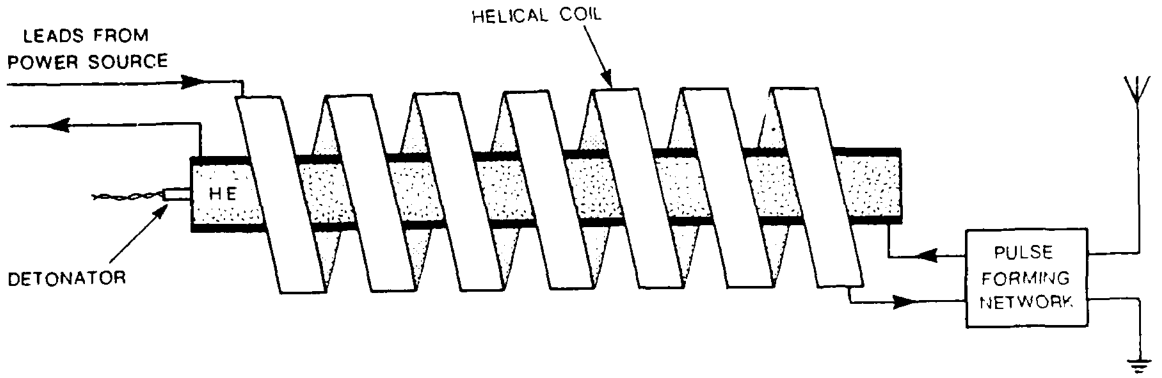
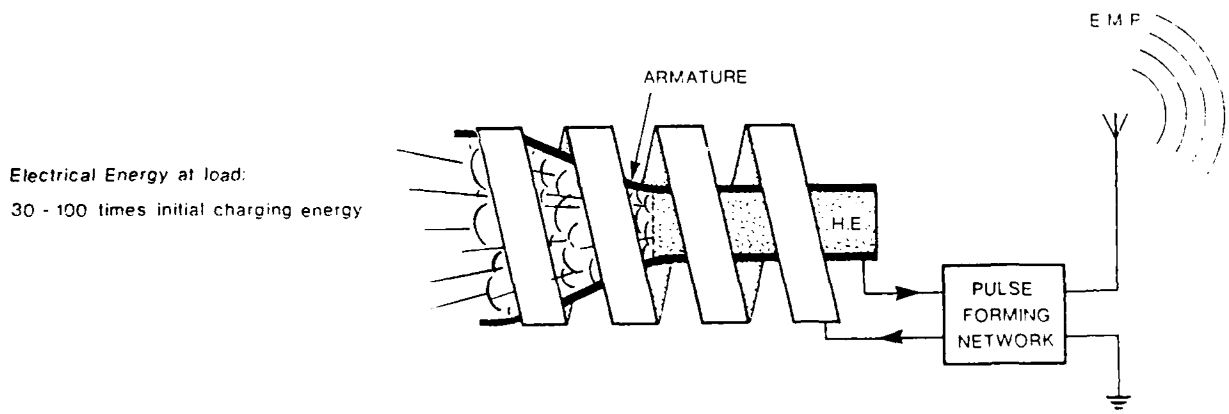


Figure 3 Sequential stages of compression for a flux compressor.



Spiral Generator prior to firing



Spiral Generator at a later stage after Explosive Detonation

Figure 4 Sequential stages of compression for a helical flux compressor.

The conversion of the explosive energy to electrical energy can be demonstrated as follows. Consider a magnetic energy storage system with initial energy E_i given by:

$$E_i = 1/2\, L_i\, I_i^2 \quad , \tag{2}$$

where L_i is the initial inductance of the storage inductor
and I_i is the current in the inductor when deformation starts.

If L_i is changed to a value L_f, and the reduction occurs very quickly so that circuit losses are negligible, the final flux linkages $\phi_f = L_f I_f$ will nearly equal the initial flux linkages $\phi_i = L_i I_i$.

In this case $$L_f I_f = L_i I_i \tag{3}$$

where L_f is the final inductance of the circuit which would be significantly smaller than I and I_f is the current immediately after the deformation is complete. From equation 3 it follows that the final energy, E_o, stored in the magnetic field is,

$$E_o = \frac{L_i}{L_f} E_i \tag{4}$$

and the theoretical energy amplification, E_o/E_i, is,

$$\frac{E_o}{E_i} = \frac{L_i}{L_f} \tag{5}$$

In practice it is found that the energy gain for a helical generator, such as that shown in Figure 4, can be expressed as [13], which allows for system losses.

$$\frac{E_o}{E_i} = \left[\frac{L_i}{L_f}\right]^{2\alpha-1} \tag{6}$$

Values in the range 0.75 to 0.80 are commonly obtained for the system specific constant, α. For a helical generator the ratio L_i/L_f would be of the order of 100, so an energy multiplication of about 16 would be expected. Energy gains of 30 and greater hav been reported [14,16].

As with explosive MHD, only a few percent of the chemical energy of the explosives is delivered as electrical energy.

Some features of flux compressors are:

(i) high energy electrical pulses are produced with extremely high power levels,

(ii) the technology is simple compared to MHD and appears to be well established

(iii) the explosive deformation of the generator coils poses severe problems in maintaining the high voltage insulation between turns,

(iv) only a single shot pulsed mode of operation appears feasible and this limits th range of applications.

(v) a primary electrical power source is needed to generate the initial current I_i; capacitor bank is commonly used,

(vi) the change in source impedance as the coil collapses during power generation reduces the efficiency of energy transfer to a load.

4.3 Choice of Power Source

Although MHD generators require a more complex set of components than do flux compressors, MHD systems are more amenable to design and suitable for the transfer of energy to a load. Because of these advantages of MHD, and the disadvantages of flux compression, i.e. the dangerous environment created by the manner in which the explosi are used and the limitation to single-shot operation, it is concluded that MHD generators are generally better candidates for power sources for high power EW systems.

A flux compressor, owing to its low mass and simplicity, may however be preferable if a very high energy single shot system is required for circumstances where it operates well away from friendly equipment.

5. MILITARY MHD SYSTEM RESEARCH

Given that MHD is the preferred method, some further details of United States military research into these generators are summarized below. The literature reveals at least 4 basic types of MHD generators. For more detailed information a small bibliography of pulse-power research has been included at the end of this report. It also provides some perspective on the historical development of pulse power.

(1) Liquid Fuel MHD Generator:

Powered by the ionised combustion products from a high power burner, eg rocket motor, this type of MHD generator can run for many seconds (or even minutes if the design permits). One advantage with this system is that it can be readily turned off or throttled up or down. One of the most notable systems was the Viking I program which produced a maximum of 1.42 MW in 2 second bursts [17,18]. The fuel in the Viking I program was liquid toluene with gaseous oxygen. This program was followed by the Viking II program which was designed to produce 10 MW [19].

(2) Solid Propellant MHD Generator:

This generator has advantages over liquid fuel types in that it is more compact in not requiring tank storage, plumbing or throttle controls. The type of propellant used is similar to that used in small rockets except that it has been seeded with cesium or potassium salts. This seeding increases the electrical conductivity of the combustion products. Such systems have achieved a power level of 2.4 MW at a propellant flow rate of 3.2 kg/s [12]. Operating periods for such systems can be the order of seconds.

(3) Solid Explosive MHD Generator:

Pulse lengths between 10 μs and 1 ms are possible with this type of system. Similar to the propellant powered systems, the explosive chemicals are seeded and the passage of the ionised explosive combustion products through the MHD channel produce the power. Because of the high energy density in explosives (5 MJ/kg) and the short operating time, very high power levels are possible. Bangerter et al [12] have demonstrated 5.7% efficiency in generating 11.8 kJ of electrical energy from 0.1 kg of C-4 explosive.

(4) Explosive Shock-tube MHD Generator:

Using a specially designed explosive cartridge filled with a noble gas, e.g. argon, this shock-tube MHD system appears to be a very promising form of a pulsed MHD generator. Detonation of the explosive generates a high velocity shock front in the noble gas which flows through the MHD channel [20]. This method provides very high power densities by virtue of achieving very high electrical conductivity in the shock front [21] and the possibility of efficiencies higher than the 1.2% reported [6].

An earlier form of shock tube generator utilized a channel in the shape of a pai of disks [22]. Shock heated cesium seeded argon gas was admitted to the centre of the disl and flowed radially outwards. The disk type channel has advantages in that it requires no insulating walls and simple field coils can be used as shown in Figure 5.

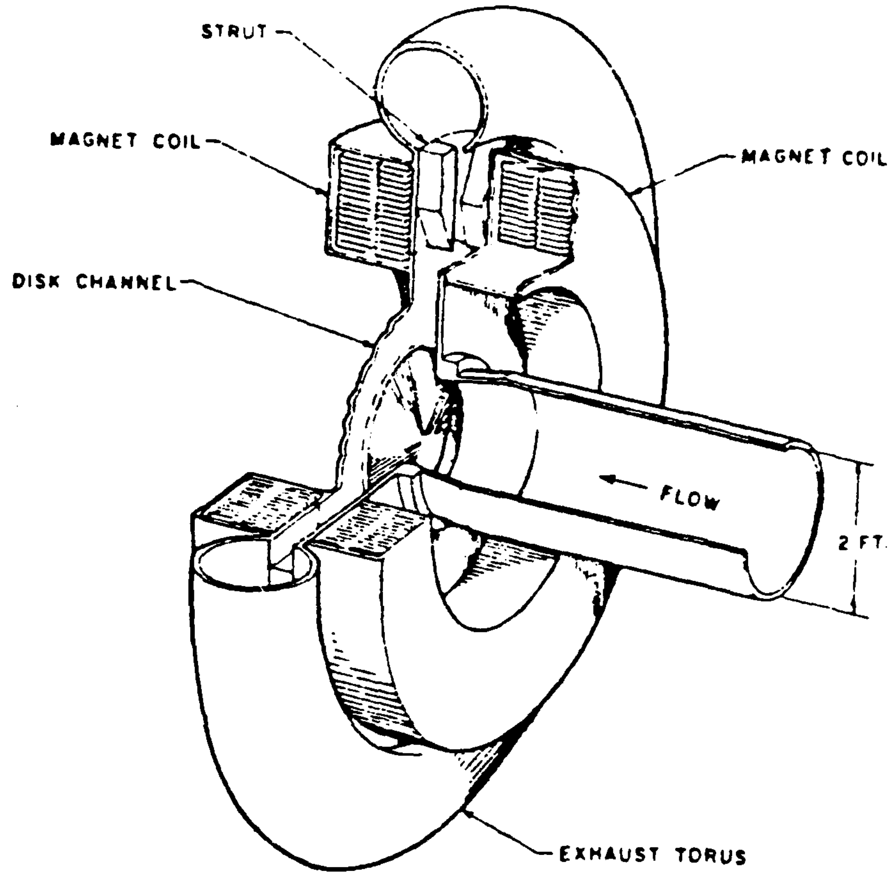


Figure 5 Cutaway View of an Experiment MHD Disk Generator, [22].

6. KEY TECHNICAL AREAS

In the preceding Sections we have demonstrated the feasibility of high power EW, given th ability to convert about 5% of the chemical energy of substances such as explosives to electrical energy. We have also briefly described the devices that achieve this conversion. The MHD generation of power from either liquid fuels, propellants or explosives is complex and technically demanding. For the practical realization of a successful MHD generator an experimentally based research program will be necessary. The key experimental and theoretical areas which have to be addressed are discussed belov

(1) Combustion Chamber Design

Irrespective of whether propellants or explosives are used to generate the plasma, confinement of the combustion products is required. Propellants require a sufficiently strong combustion chamber and nozzle, whereas explosive plasma generation, with its inherently higher power levels, needs a very strong steel breech block behind which a detonated high explosive cartridge would be contained. Such cartridges would hold specially-contoured explosives to generate the correct plasma shape. In the case of shock-tube type generators, the explosive and noble gas filled cartridge also contains a closing plug. The purpose of the plug is to allow only the heated and shocked noble gas to enter the MHD channel by stopping all explosive contaminants.

(2) Plasma Seeding

Theoretical predictions on seeding requirements to achieve high electrical conductivity in the plasma have not always been confirmed in experiments [23]. Many experiments have been performed to characterise the amount of seeding and the chemical composition of the fuel [24]. Plasma conductivity is very important as it directly effects power and efficiency of the system.

(3) Shock Tube Type Generators

The temperatures and pressures generated in the shock waves give rise to non-ideal plasmas. A significant theoretical and experimental effort would be required to characterise plasma conductivity, magnetic field interaction and boundary layer effects. Generation of appropriately-shaped waves is necessary and this entails research in the configuration of the combustion chamber.

(4) The MHD Channel

Using explosives or propellants, the high temperature, high velocity plasmas (which could well be corrosive) place very demanding requirements on the channel materials.

Materials used for the insulating walls have included phenolic resins and ceramics. Alumina has been used with some success. The main problems with the insulating walls appear to be surface erosion and surface contamination which destroys the insulating property of the wall.

Channel electrodes have used metals such as aluminium and copper. A more exotic material used has been stabilised zirconia which is an electrolytic conductor when it is hot. Pyrolytic graphite has been considered because it has a good anisotropic thermal conductivity. Erosion of the electrodes is a problem as is their design for efficient power extraction and cooling. These designs can be quite complicated to model and to fabricate.

The shape of the channel is also very important, not only for efficient flow of the plasma, but for the interaction of the plasma with the magnetic field. The shape of the inlet throat (Fig. 2) to the MHD channel determines pressure, velocity and the shape of the plasma front. Any fringing of the magnetic field into this area will also have to be considered in the throat design. The end of the channel must have a well designed diffuser (Fig. 2) so the expansion of the exhaust gases does not cause back pressures that can produce stagnation in the plasma flow.

(5) Magnetic Field

The shape and strength of the magnetic field which passes between the channel electrodes directly influences the level of power generated. In order to maximise the magnetic flux density between the electrodes, complex "saddle-shaped" windings have been used. Fringing of the magnetic field into the entrance throat of the channel needs to be avoided or at least minimised and this requirement can further complicate design and fabrication.

(6) Radio Frequency Generator

High efficiency, small size and low mass are the obvious desirable features for the generator. However, it can be readily appreciated that a tube which produces 125 kJ of R energy at 50% efficiency, as suggested in Section 2, would also have to absorb 125 kJ. Dissipation of this energy would mean forced air or water cooling. Furthermore, such a tube would probably operate at voltages of the order of 100 kV or more. Kehs et al [25] have described a reflex triode which produces peak power as high as 3 GW at X-band. Thi device was driven by a flash x-ray power supply that produced a 20 kA average current pulse, 25 ns wide with a 1 MV peak accelerating voltage. Also mentioned in the same pape were data for a magnetron that also produced 1 GW, but at S-band, requiring only 360 kV and a 12 kA, 30 ns pulse. Efficiencies of the two RF generators were 5 and 35 percent respectively. The size of the RF generators were not reported by Kehs et al. Bekefi et [26] reported a realistic electron beam magnetron which achieved 1.7 GW of radiated pow in a 30 ns pulse at a frequency of 3 GHz. This device was only 72 mm long with a diamet under 100 mm. The device only needed 0.8 T magnetic field and achieved an efficiency o 35%.

An interesting alternative to tube type RF generators is to use solid state devices [27]. These would require voltages of the order of 100V, but current would need t be in the MA range.

(7) Transfer and Conditioning of Generator Energy

The voltage and current outputs for highly efficient MHD conversion do not match the requirements of RF oscillators. Special transformers with very tight coupling may need t be developed for this purpose.

Other topics that would need to be addressed (not necessarily sequentially) for high power EW applications include:-

(i) Analysis of possible application scenarios to identify range, power, energy and frequency-band, size and weight requirements.

(ii) Comparison of weapon effectiveness with alternative, conventional systems.

(iii) Selection of suitable antenna structures required for different applications.

(iv) Integration of energy-conversion and antenna systems with weapon platforms and associated shielding from rearward antenna radiation.

(v) Estimation and validation of disruption and damage threshold levels for representative target devices and systems.

7. SUMMARY AND CONCLUSION

Electronic warfare is a most important element of military technology. Although a capacity to cause temporary disruption is useful, the most effective result in battle conditions is to permanently damage enemy equipment. A key requirement for this form of electronic warfare is a compact source of very high power. The study concludes that MHD generation is the primary candidate for powering such potential EW systems. Four types of MHD generators have been identified from a literature search. In comparisons between explosive, propellant and fuel-based systems, explosive-powered MHD generators achieve the highest power levels. The report has identified critical areas of MHD research requiring experimental and theoretical effort.

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10. SYMBOLS TABLE

α	=	system specific constant
B	=	magnetic field
e	=	electronic charge
E	=	energy
k_B	=	Boltzmann's constant
L	=	inductance
P_D	=	maximum power density in MHD duct
T	=	plasma temperature
σ	=	electrical conductivity
v	=	plasma velocity
I	=	current
ϕ, ϕ_r, ϕ_f	=	magnetic flux
ϕ_E	=	energy flux density
U_i	=	ionisation energy for the ith state of ionisation

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ABSTRACT

Electronic warfare (EW) is an extremely important element in modern militar conflicts. One form of EW involves jamming, where in general the effectiveness increase with the power level that can be employed. Within the constraints of the upper power li it would seem to be possible to raise power levels to the point where components are damaged. The required high powers for such EW functions can be produced by compact magnetohydrodynamic (MHD) power sources using fuels such as explosives and propellant Some indicative applications are discussed and areas for research are identified.

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